



High-Resolution Ambient Record of Aerosols over Delhi and Associated Typical Health Effects

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Abstract

Atmospheric aerosols, soon after their emission, may experience changes in its chemical composition, mass concentration, size, and its optical properties. These changes are dynamic in nature and occur over a short period of time. Since aerosols play a critical role in human health effects, cloud microphysics, hydrological cycle and climate perturbations, it is therefore of paramount importance to understand both qualitatively and quantitatively all the major changes, which an ambient particle could experience during its residence time in the atmosphere. High-resolution measurements (i.e. real-time measurements) are being carried out worldwide to capture any high-frequency changes in aerosol characteristics. In this study, we discuss the observations based on an open-access high-resolution data set retrieved from the Central Pollution Control Board (CPCB) for a location in central capital Delhi. Along with the particulate matter (PM) data, we also discuss some of the gaseous species owing to the reason that these gases influence the aerosol behaviour and its budget due to coating and secondary aerosol formation. The source strengths are highly variable (in both space and time) in Indo-Gangetic Plain (IGP) mainly due to industrial activities and seasonal influence of biofuels and biomass burning emission. This chapter presents a case study

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highlighting some of the important observations on temporal variability and processes from high-resolution atmospheric data set of aerosols and reactive gases. We also present here a review on the health effects of outdoor and indoor aerosol pollution.

Keywords

Aerosols · Trace gases · Urban air pollution · Health effects

5.1 Introduction

Air pollution is the presence of any substance in the air at such concentrations, which are detrimental not only to the human beings, flora and fauna but also to the several components of the environment (Chakraborty et al. 2017; Choudhary et al. 2018). Air pollution is one of the major causes for degradation of environment (Yadav and Rajamani 2004). It occurs either from natural sources like volcanic eruptions, forest fires, sea spray, wind blown dust and pollen grains or can be as a result of various anthropogenic (human) activities like agricultural waste burning, vehicular emissions, power plants, and industrial emissions (Fig. 5.1). Air pollutants usually exist as tiny solid and liquid (e.g. dust, oil droplets and particulate matter), gases (e.g. NO_x , SO_2 and O_3) and semi-volatile species [e.g. PAHs: polycyclic aromatic hydrocarbons] (Rajput et al. 2014b). It has been widely realized that air pollution has

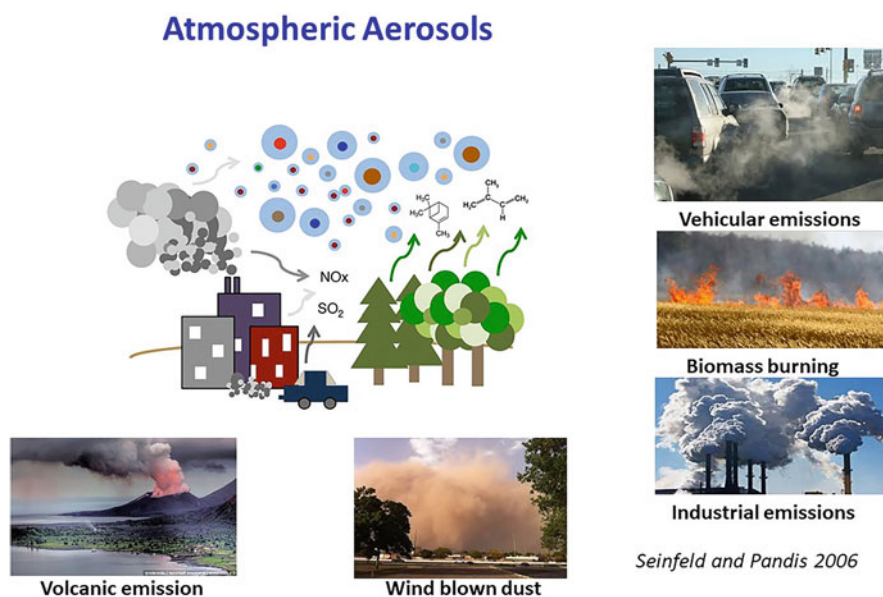


Fig. 5.1 Various sources (primary emissions and secondary formation) of ambient aerosols (also known as particulate matter: PM) (Seinfeld and Pandis 2006; Rajput et al. 2011, 2018a, b)

emerged not only as a local problem but also as a regional and a global problem (Izhar et al. 2018). Air pollution is widely being understood as one of the biggest environmental health risk factors of this century (Dockery et al. 1993; Rajput et al. 2014a; Schwartz 1995). Anthropogenic activities such as rapid industrialization, unrestricted population growth and increasing urbanization contribute increasingly to elevated emission rates of various air pollutants—among these, specifically higher levels of particulate matter (PM₁₀ and PM_{2.5}), sulphur dioxide (SO₂), nitrogen oxides (NO_x), carbon monoxide (CO) and ozone (O₃)—leading to not only the degradation of the environment and climate change but also having a debilitating effect on human health (Dey et al. 2012; Pant et al. 2016). Simultaneously, over two-thirds of rural Indians caught in the ‘chulha trap’ use biomass fuels such as wood, twigs and dung cake to meet their cooking and heating needs, resulting in smoke-filled homes causing extremely high levels of exposure to the residents. Air pollution is especially severe in many developing parts of the world, which also happen to be very fast-growing urban regions contributing higher levels of pollution and are therefore subject to higher exposure. According to the World Health Organization’s (WHO) figures, 97% of the cities in the low- and middle-income countries (LMICs), which have more than 100,000 inhabitants, do not meet WHO air quality guidelines (WHO 2018a). In the year 2016, ambient air pollution is estimated to have caused 4.2 million premature deaths worldwide, of which 91% occurred in LMICs (WHO 2016).

The atmospheric aerosol (aka particulate matter) ranges from 0.001 to 100 µm in aerodynamic diameter. Having various sources of origin and different chemical composition, they are an intricate combination of small and big particles (Kumar et al. 2017). They can mainly be sub-divided into two parts: primary and secondary. Primary aerosols are those that are directly produced and emitted into the atmosphere from identifiable sources like vehicles, industries, desert areas, construction activities, fossil fuel combustions, and road dust. They consist of black carbon (BC), crustal elements and organic compounds of high molecular mass released from combustion sources, etc. (Sorathia et al. 2018). *Secondary organic* aerosols (SOA) are those that form when condensation of volatile organic compound (VOC) oxidation products takes place (Rajput et al. 2013; Seinfeld and Pankow 2003). Secondary/aged aerosols are either organic or inorganic that affects the physico-chemical properties of the aerosols (Rajput et al. 2018a, b). Once produced, they grow to different sizes and can have different composition due to several physical and chemical modifications like coagulation, polymerization, photolysis, structural reorganization, and phase alteration and these processes are defined as atmospheric ageing (Fuzzi et al. 2006). SIAs (secondary inorganic aerosols) are formed from the chemical reactivity of gases like SO₂, and NO₂ and NO (collectively known as NO_x) leading to the formation of particulate sulphate and nitrate (Rajput et al. 2016). A recent study (Rajput and Gupta 2020), through causal modelling, has shown that for every 10-unit change in O₃ concentrations the SOA formation increases by ~3.2% during daytime under prevailing long-range transport of biomass burning emissions from upwind IGP. Overall, the main composition of an atmospheric aerosols includes crustal matter (mineral dust); sea salt which includes sulphate, magnesium,

sodium and chloride; secondary particles like nitrate, sulphate and ammonium; trace metals like vanadium, chromium and lead; and carbonaceous material which includes both elemental and organic carbon and liquid water content (Senfield and Pandis 2006).

Also, depending upon the size of the particles, aerosols are classified into various categories. TSPs (total suspended particulate matters) are those whose aerodynamic diameter (d) is $\leq 100 \mu\text{m}$ (aerodynamic diameter of a particle is the diameter of a unit density sphere ($\rho = 1 \text{ g/cm}^3$) having the same terminal velocity as the particle of interest (Senfield and Pandis 2006), PM_{10} (coarse mode) whose aerodynamic diameter (d) is $\leq 10 \mu\text{m}$ and $\text{PM}_{2.5}$ (fine fraction) whose aerodynamic diameter is $\leq 2.5 \mu\text{m}$. The fine fraction particles are further classified into nucleation mode ($d \leq 0.01 \mu\text{m}$), Aitken mode ($0.01 < d < 0.1 \mu\text{m}$) and accumulation mode ($0.1 < d < 1 \mu\text{m}$) (Raes et al. 2000). Coarse mode particles are formed from various mechanical processes like wind-blown dust, sea salt spray, cement dust, milled flour and pollen, but the fine particles are mainly formed from the various combustion processes (causing formation of black carbon, smoke, etc.) and condensation processes or secondary conversion of gases into the particulates (Rajput et al. 2016).

Aerosols influence the quality of life by affecting health, visibility and the environment at a very profound level (Posfai and Buseck 2010). Various epidemiological studies show that the mortality and morbidity rate in human beings increases with increase in the concentration of aerosols, especially correlated with the fine fraction particles (Geller et al. 2002; Srivastava and Jain 2007; Dockery and Brunekreef 1996; Peters et al. 2000; Neas et al. 1999; Schwartz 1995; Korrick et al. 1998). Among those most affected are the women, children, senior citizens, and the subjects with respiratory illness.

Aerosols play an important role in the climatic system of the Earth and the biogeochemical cycle of oceans (Mahowald et al. 2005). Aerosols affect directly the Earth's atmospheric radiative balance by scattering and absorbing incoming solar radiations, resulting in warming or cooling of the atmosphere. For instance, black carbon absorbs solar radiation and makes the global climate warm (Ramanathan and Carmichael 2008) and organic aerosols (net effect) scatter light, which led to reduction in incoming solar energy (Rudich 2003). Aerosols affect the climate indirectly by acting as CCN (cloud condensation nuclei) and IC (ice nuclei), i.e. act as nuclei for the condensation of water vapour and ice crystal (Novakov and Penner 1993; Spracklen et al. 2011). Indeed, if there were not any atmospheric aerosols, clouds would not be formed and would have resulted in no precipitation. Due to the increase in anthropogenic activities, burden on global mean aerosol concentration has changed considerably (Rajput et al. 2011). In order to enumerate these effects in a better way, a very good understanding of the formation, composition and transformation of aerosols is desired. Dry and wet scavenging processes are the two main removal pathways of aerosols from the atmosphere. Generally, the larger particles with $d > 1 \mu\text{m}$ are removed by gravitational settling, but this process becomes less efficient as the particle size reduces. Particles with $d < 1 \mu\text{m}$ can be removed efficiently by the wet deposition (Rajeev et al. 2016).

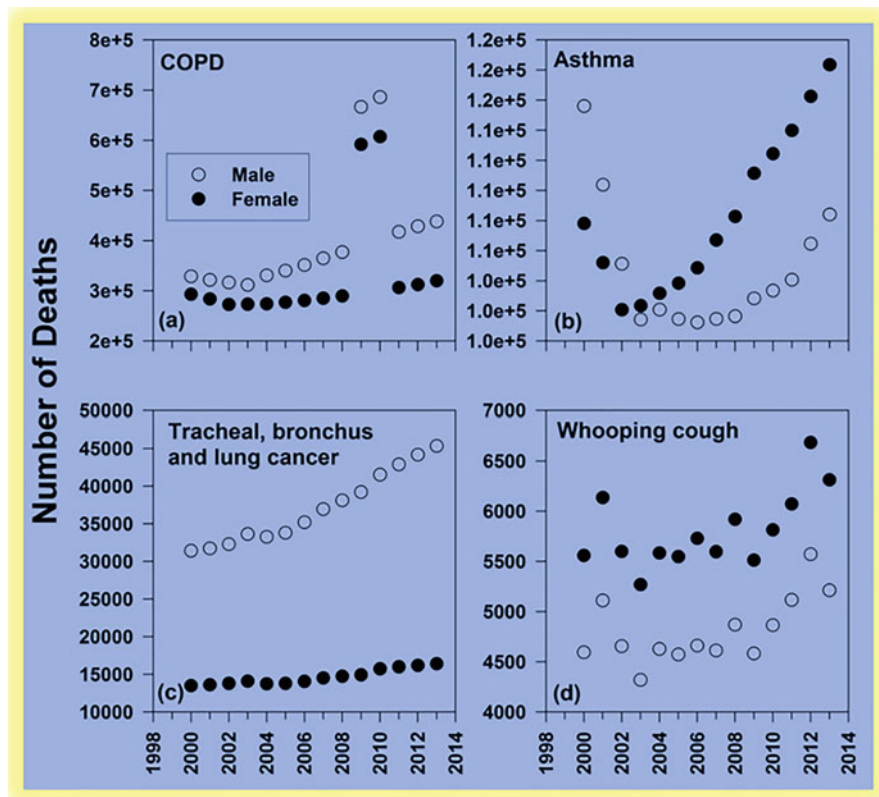


Fig. 5.2 Cause- and gender-specific mortality estimates for Indian region based on Global Burden of Disease data set (GBD 2015; Rajput et al. 2019)

Worldwide research on exposure assessment of ultrafine and fine particles has suggested severe human health impacts due to inhalation (Nazarenko et al. 2014; Singh and Gupta 2016; Asbach et al. 2017; Dandona et al. 2017). A near-continuous assessment on morbidity and mortality from major diseases, injuries and risk factors is being carried out through Global Burden of Disease (GBD) research programme (GBD 2015). GBD estimates (Fig. 5.2) suggest that number of mortalities in India is rising year by year due to COPD, asthma, TBL cancer and whooping cough, among others.

Integrating the data set on mortality (Fig. 5.2), it has been inferred that death of about one million people (including both male and female subjects) in 2013 year (in India) was caused due to respiratory diseases. Furthermore, decadal monitoring of GBD data set suggests that premature mortality of males is more pronounced due to COPD and TBL cancer (among the respiratory diseases), whereas higher deaths of females were found due to asthma and whooping cough (Fig. 5.2). One of the plausible reasons suggested for observing higher mortality due to asthma and whooping cough in females relate to the fact that most of the Indian women are

housewives and are therefore exposed for prolonged period to indoor air pollution and fresh emissions from biofuels as compared to the men (Parikh et al. 2001; Padhi et al. 2017).

5.2 Air Quality Guidelines

The air quality guidelines recommended by different organizations viz. World Health Organization (WHO), European Union (EU) and Indian region are listed in Table 5.1.

Air pollution kills an estimated seven million people worldwide every year. WHO data show that 9 out of 10 people breathe air containing high levels of pollutants. WHO is working with many countries to monitor air pollution and improve air quality. From smog hanging over cities to smoke inside the home, air pollution poses a major threat to health and climate. The combined effects of ambient (outdoor) and household air pollution cause about seven million premature deaths every year, largely as a result of increased mortality from stroke, heart disease, chronic obstructive pulmonary disease, lung cancer and acute respiratory infections. More than 80% of people living in urban areas are exposed to air quality levels that exceed WHO guideline limits, with low- and middle-income countries (LMICs) suffering from the highest exposures, in both indoors and outdoors.

5.3 Methodology

5.3.1 Air Pollution Monitoring in Delhi

Indian region, especially northern part, has experienced daunting challenges due to air pollution—according to several researchers, it kills every year more than one million in the country (Chatterjee 2019; Rajput et al. 2019). Many cities in India

Table 5.1 Air quality guidelines from World Health Organization, European Union and NAAQS (India)

Pollutant	WHO		EU		Indian	
	24 hr mean	Annual mean	24 hr mean	Annual mean	24 hr mean	Annual mean
PM _{2.5} (µg/m ³)	25	10		25	60	40
PM ₁₀ (µg/m ³)	50	20	50	40	100	60

Interim targets(IT) by WHO aimed at promoting a gradual shift from high to lower concentrations.

IT for PM_{2.5} (annual)

IT-1 – 35 µg/m³
 IT-2- 25 µg/m³
 IT-3- 15 µg/m³

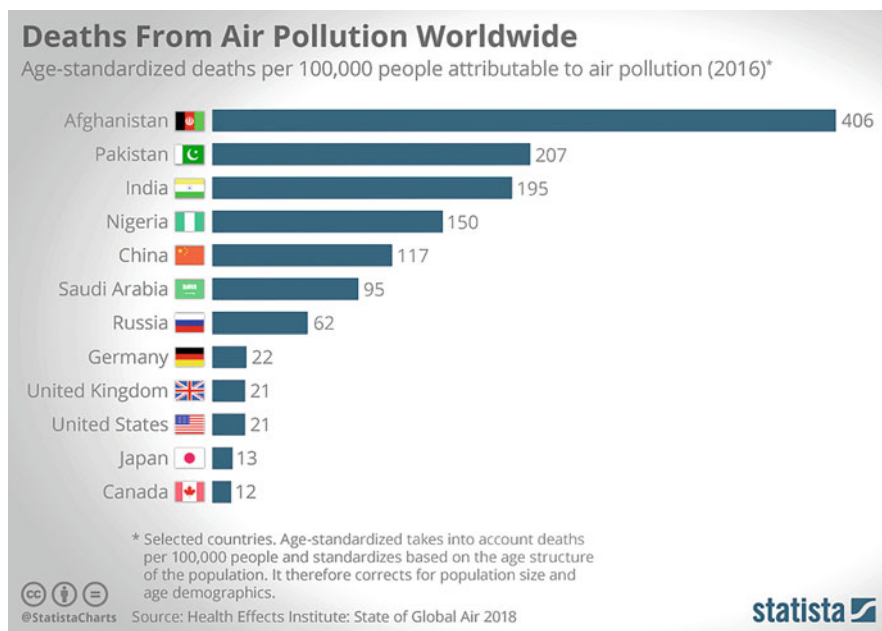


Fig. 5.3 A global scenario on air pollution caused mortality data from various countries (<https://www.statista.com/chart/13575/deaths-from-air-pollution-worldwide/>)

have exceeded over 5 times of the $PM_{2.5}$ level recommended by the WHO guidelines. Fine particulates ($PM_{2.5}$), comprising primarily of mineral dust, secondary aerosols and combustion products, are ~ 20 times smaller than a human hair, and they cause stroke, heart disease, chronic obstructive pulmonary disease, and lung cancer (WHO 2016, 2018b). In total, 90% of the world's population breathe harmful air (<https://news.un.org/en/story/2018/05/1008732>). A global scenario on air pollution led mortality from various countries is shown in Fig. 5.3.

India is making some progress in this area. The National Clean Air Programme aims to reduce air pollution levels by up to 30% by 2024. The country is also planning what it calls the world's largest expansion of renewable energy by 2022.

A recent 'world air quality report', published by AirVisual (2018), has reported a list of 20 most polluted cities in South Asia, and 16 of these are cities in India (Fig. 5.4). Delhi is the capital of India, and it is one of the most polluted cities in the world.

The heterogeneity in $PM_{2.5}$ levels and other gaseous pollutants is dependent on the location (Zikova et al. 2017). Many previous studies have been carried out to investigate the air pollution over Delhi through offline measurements. Since 2017, CPCB initiated continuous ambient air quality monitoring measuring air quality on a near-real time to hourly time interval resolution. The best part of these measurements by CPCB is that the data set is open source. The regulatory bodies and public organizations have deployed a series of instruments based on the federal reference

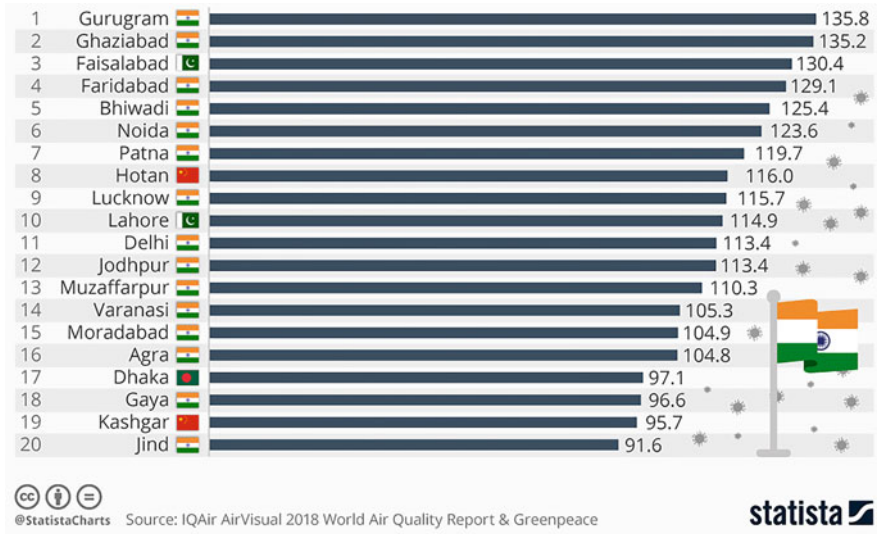


Fig. 5.4 Regional scenario of air pollution (annual average PM_{2.5} in year 2018) in Delhi and nearby cities in India and in neighbouring countries. Source: AirVisual (2018)

method (FRM) and federal equivalent method (FEM) for an accurate and reliable air quality measurements in Delhi (DPCC 2017). A total of 26 Continuous Ambient Air Quality Monitoring Stations (CAAQMS) have been set up to help improve air quality data sets and assess the spatiotemporal variabilities in the abundance of pollutants and their source contributions (<http://www.dpccairdata.com>).

This chapter also embodies observations and discussions on the variability, effects and the understanding of criteria air pollutants. This work on detailed characterization of the air masses in Delhi documents on the following: (1) temporal variability of air pollutants on an hourly, weekly and seasonally basis; (2) abundance of primary and secondary pollutants and their relative abundances; and (3) application of conditional probability function (CPF) and potential source contribution function (PSCF) to look into the new insights of air pollution over Delhi.

5.3.2 Study Site

To assess the ambient air quality in urban area of Delhi, the Mandir Marg (MM) site was selected (Fig. 5.5).

MM is situated in the central part of Delhi, and it is 200 m away from the ring road, and the site has an influence from local emissions such as light duty/heavy duty vehicle activities. At MM site, a real-time beta-attenuation monitor (BAM, Ecotech, AECOM Group, Australia) and gases monitor (Ecotech, AECOM Group, Australia) are installed by the CPCB for measuring criterion pollutants.

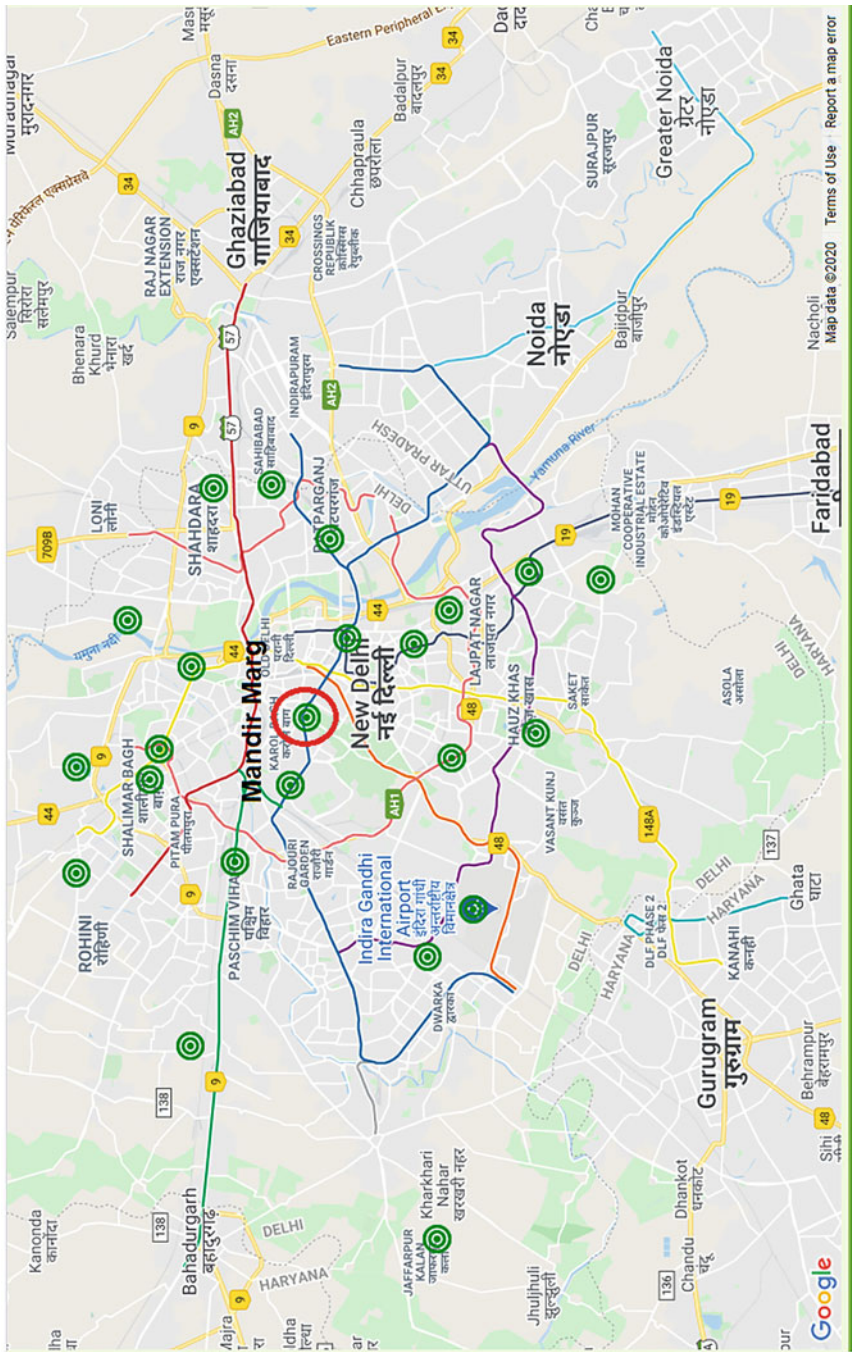


Fig. 5.5 Air quality data set in this work have been retrieved from CAAQM station (i.e. Mandir Marg; MM). Source: Real-Time Ambient Air Quality Data of Delhi (DPCC)

5.3.3 Data Source and Study Period

The hourly concentrations of particulate matter (PM_{2.5} and PM₁₀) and other pollutants along with the meteorological parameters (wind speed, wind direction, temperature, and relative humidity) were obtained from the CPCB online portal for air quality data dissemination (<https://app.cpcbcr.com/ccr/#/caaqm-dashboard-all/caaqm-landing>). In this study, concentrations of these pollutants were analysed for the time period of 1 year from 01 January 2018 to 31 December 2018.

5.3.4 CBPF Analysis

In order to identify the local sources of pollutants, the conditional bivariate probability function (CBPF) analysis was performed. The CBPF was calculated using air pollutants by coupling of conditional probability function (CPF) with wind speed as a third variable, distributing, measured pollutant concentration to range of wind sector bins. CBPF is defined as follows:

$$\text{CBPF}_{\Delta\theta, \Delta u} = \frac{m_{\Delta\theta, \Delta u} \downarrow c \geq X}{n_{\Delta\theta, \Delta u}}$$

where $m_{\Delta\theta, \Delta u} \downarrow c \geq X$ is the number of samples while wind is blowing in the wind sector ' $\Delta\theta$ ' with wind speed interval ' Δu ' having concentration ' c ' greater than a threshold value, ' X '; and $n_{\Delta\theta, \Delta u}$ is the total number of samples observed in that wind direction for a given speed interval. The threshold criterion was chosen at the 50th or 75th percentile of pollutant concentration. CBPF analysis was performed by openair R package (Carslaw and Ropkins 2012) in R-studio (version 3.1.1; R Core Team, 2014) statistical software. More details about the method are described in Uriarte and Carslaw (2014).

5.3.5 PSCF Analysis

Air mass backward trajectories (AMBTs) were retrieved for each day at intervals of 3 h for the duration of 120 h during the study period in year 2018 using National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Rolph et al. 2017). The spatial resolution of the data is $1^\circ \times 1^\circ$, and the arrival heights of AMBTs were 500 m above the ground level. In this study, openair package in R has been utilized to download back trajectories. The functions and codes for downloading the monthly meteorological file from HYSPLIT PC model and merging every 3-h back trajectory end-point files (e.g. at MM site in this study) are discussed in openair R package manual. Furthermore, the potential source contribution function (PSCF) was also performed using the openair R package (Carslaw and Ropkins 2012).

5.3.6 Results and Discussion

Figure 5.6 shows the time-series plots (hourly variation) of PM₁₀, PM_{2.5}, CO, NO₂, NO, and SO₂ over the entire study period. The relevance of discussing here some of the gaseous species lies in the fact that they are connected with the emission source of PM and/or contribute to its burden through chemical reactivity (of these gases) and formation of secondary aerosols. The high concentrations of PM₁₀ were observed in various episodes with frequent peaks in summer (March, April, May, and June 2018), and few peaks during the autumn season (November 2018). The PM₁₀ mass concentrations exceeded over 75% of the National Ambient Air Quality Standards (NAAQS), attributable partially due to high load of mineral dust near the site. The highest mean ($\mu \pm 1 \sigma$) concentration of PM₁₀ was observed as $292 \pm 116 \mu\text{g m}^{-3}$ in winter, followed by $218 \pm 126 \mu\text{g m}^{-3}$ in autumn (post-monsoon), $182 \pm 101 \mu\text{g m}^{-3}$ in summer and $126 \pm 86 \mu\text{g m}^{-3}$ in monsoon, respectively.

In contrast, the elevated levels of PM_{2.5} were observed during autumn (5 and 13 November 2018) and winter (22–24 and 29 December 2018) compared to summer and monsoon. The high concentrations of PM_{2.5} during autumn and winter are attributable to the emissions from regional agriculture residue burning and local burning for space heating. The PM_{2.5} concentrations exceeded over 55% as compared to NAAQS likely due to the anthropogenic sources (long-range transport of agricultural waste burning emissions, coal combustion, local biomass/waste burning, and vehicular emissions). The hourly mean PM_{2.5} concentrations were observed as $192 \pm 92 \mu\text{g m}^{-3}$ during the winter season, followed by autumn ($159 \pm 147 \mu\text{g m}^{-3}$), summer ($79 \pm 55 \mu\text{g m}^{-3}$) and monsoon ($49 \pm 32 \mu\text{g m}^{-3}$), respectively (Fig. 5.6). The winter months are associated with low temperatures, low solar radiation, low mixing heights, and calm winds. All of these conditions are favourable for the accumulation of pollutants, and thus, leading to high concentrations of PM. The geographical setting of the region also plays a critical role in the dispersion/accumulation of air pollution.

High peaks of CO concentrations were found mainly during the winter (26–31 January 2018). The highest mean CO level was observed as $2.6 \pm 4.8 \mu\text{g m}^{-3}$ during the winter season, followed by autumn ($1.8 \pm 1.4 \mu\text{g m}^{-3}$), summer ($1.1 \pm 0.8 \mu\text{g m}^{-3}$), and monsoon ($0.5 \pm 0.3 \mu\text{g m}^{-3}$) (Fig. 5.6). During winter and autumn seasons, local and regional source activities [burning of leaves and woods, and long-range transport of emissions from agricultural residue burning and the burning for heating purpose in winter] along with the lower boundary layer height could be the possible reasons for high concentrations of CO.

A near similar trend was observed for NO₂ and NO concentration during the study period at MM site. However, the highest NO₂ and NO concentrations were observed during night and early morning in winter and autumn season likely due to increasing heavy duty diesel vehicle emission, atmospheric chemistry and low mixing height. The highest mean NO and NO₂ concentrations were $96 \pm 146 \mu\text{g m}^{-3}$ and $74 \pm 39 \mu\text{g m}^{-3}$ during winter season of 2018, followed by autumn ($103 \pm 136 \mu\text{g m}^{-3}$ for NO; $79 \pm 43 \mu\text{g m}^{-3}$ for NO₂), summer

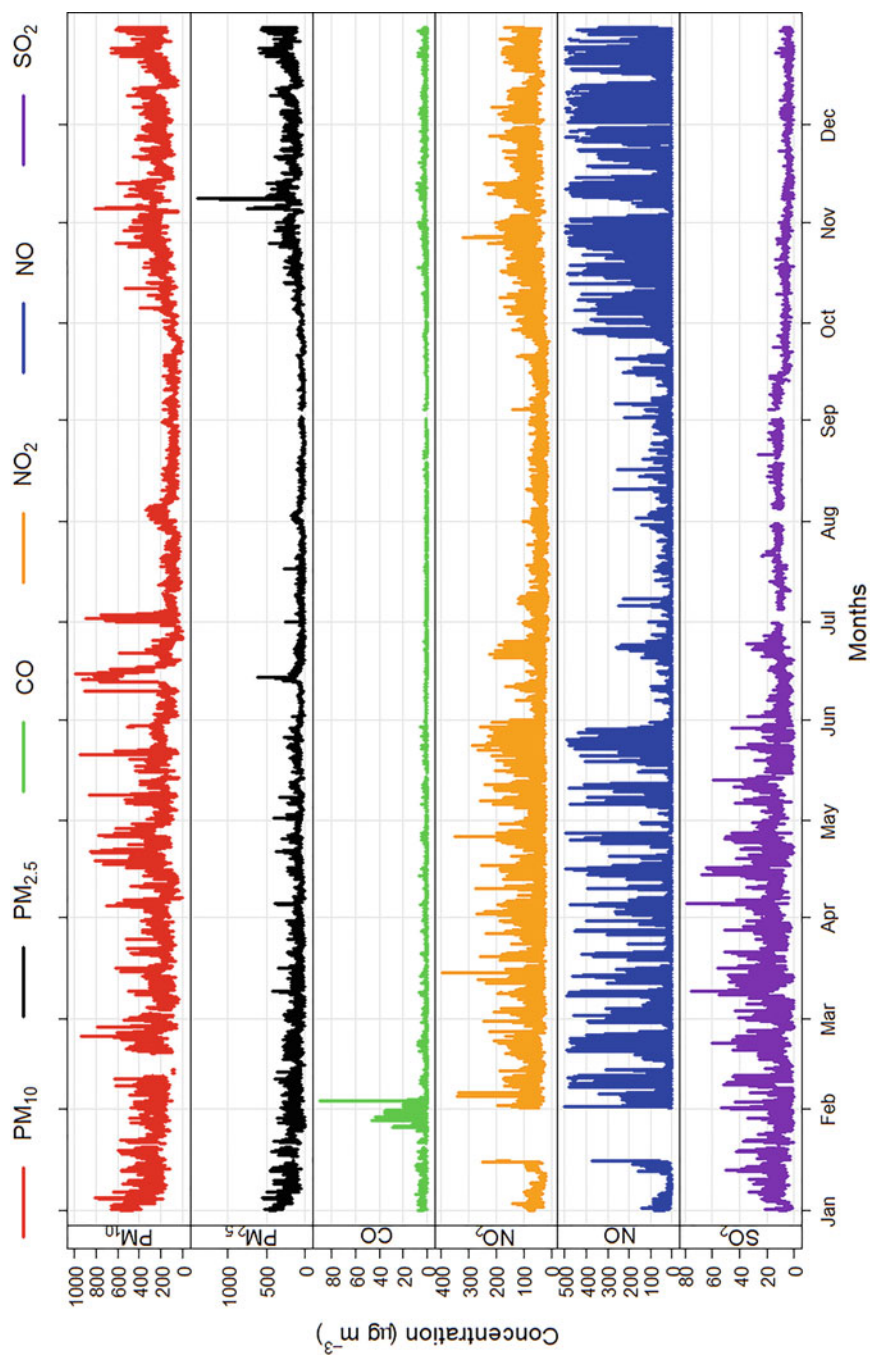


Fig. 5.6 Time series of PM_{10} , $PM_{2.5}$, CO, NO_2 , NO, and SO_2 monitored over an urban site (Mandir Marg) of Delhi during the year 2018

($47 \pm 93 \mu\text{g m}^{-3}$ for NO; $65 \pm 43 \mu\text{g m}^{-3}$ for NO₂), and monsoon ($21 \pm 39 \mu\text{g m}^{-3}$ for NO; $38 \pm 20 \mu\text{g m}^{-3}$ for NO₂) seasons, respectively (Fig. 5.6). Interestingly, it is noted that NO level is lower in summer and monsoon as compared to NO₂ level, which indicates the influence of photo-chemistry in regulating the abundance of NO_x species.

The elevated peaks of SO₂ were observed in winter through summer (March, April, and May), and then, declining levels are observed in monsoon and autumn seasons. The highest mean SO₂ concentration was observed as $16.2 \pm 10.3 \mu\text{g m}^{-3}$ during summer, followed by winter ($11.0 \pm 9.1 \mu\text{g m}^{-3}$), monsoon ($10.9 \pm 2.0 \mu\text{g m}^{-3}$), and autumn ($5.4 \pm 1.7 \mu\text{g m}^{-3}$) (Fig. 5.6).

5.3.7 PM_{2.5}/PM₁₀ Ratio

Figure 5.7 shows the calendar plot of hourly mean PM_{2.5}/PM₁₀ ratio at an urban site (MM) of Delhi. A high ratio of PM_{2.5}/PM₁₀ varying from 0.8 to 1.0 during the autumn and winter season has been observed in this study. The high ratios suggest the predominant impact of anthropogenic emissions and the intense atmospheric reactions leading to enhanced formation of secondary aerosol during the high PM_{2.5} pollution episodes. Furthermore, the PM_{2.5}/PM₁₀ ratios were found in the range of 0.2–0.4 during the summer months at the study site, which plausibly indicates that coarse particles were more prevalent in the summer season. This observation has

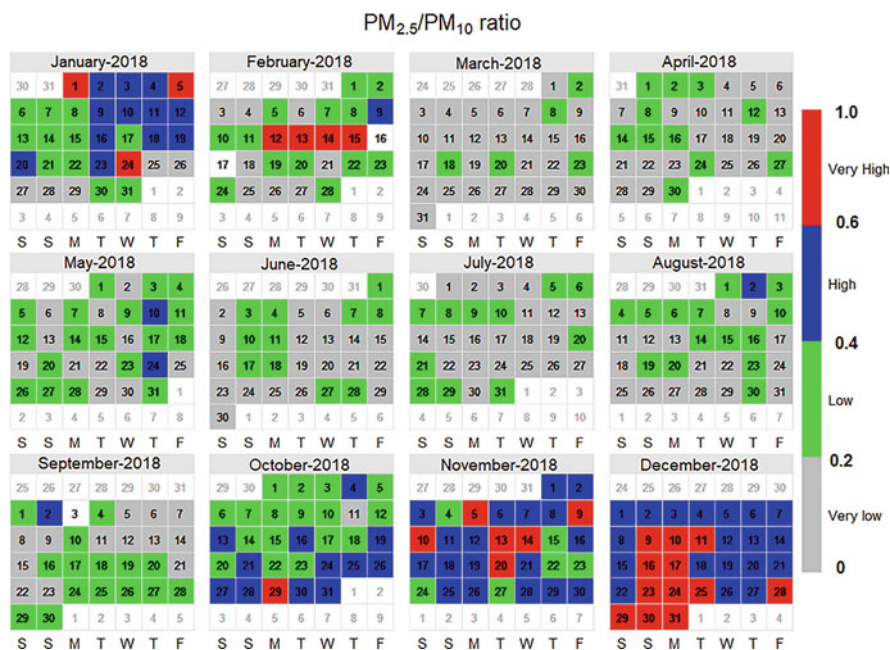


Fig. 5.7 Calendar plot of PM_{2.5}/PM₁₀ ratio over an urban site (Mandir Marg) in Delhi during 2018

linkage to enhanced mineral dust resuspension during the drier and hot summer season.

5.3.8 Influence of Meteorology

Besides atmospheric chemistry, the meteorological factors can also influence the level of air pollutants. Therefore, in order to understand the transport and the variabilities of criteria pollutants, conditional probability function (CPF) using wind speed and direction was analysed for the two high pollution witnessing seasons (winter and autumn). We plotted CPF by openair R package (Carslaw and Ropkins 2012) in R-studio (version 3.1.1; R Core Team, 2014) statistical software. More details about the functions are described in openair manual (Carslaw and Ropkins 2012).

The CBPF plots for diagnostic ratios ($PM_{2.5}/PM_{10}$, CO/NO_x and SO_2/NO_x) are shown in Fig. 5.8 for two different seasons [top panel (winter) and bottom panel (autumn)]. Concisely speaking, one of the unique features from CBPF plots for all the assessed pollutants or its ratios herein is that their variability pattern is by and large governed by the winds from south-west to the south-east direction.

5.3.9 PSCF Analysis

Further, the PSCF approach helps to establish the comparative importance of regional and local sources by determining the contributions of potential source regions influencing the air pollution at the receptor site. The PSCF analysis also segregates the relevant back trajectories along with species concentrations at the receptor site. The PSCF plots for the $PM_{2.5}$ are shown in Fig. 5.9 and the colour scale shown in each of these maps is a PSCF probability, indicating the possibility of source origin of a given species, which is measured at the receptor site. Threshold criteria were chosen at 75th percentile of pollutants for identifying the specific sources. For $PM_{2.5}$, PSCF analysis identified regional source locations in north-western region encompassing areas from IGP region such as Delhi, Punjab, Haryana and northern Pakistan, especially in winter and autumn seasons. Some parts of Uttar Pradesh also contributed $PM_{2.5}$ in autumn season (Fig. 5.9). It should be noted that the highest $PM_{2.5}$ was associated with low winds. In a recent study (Rajput et al. 2021), it has been shown that ~73% of the total PM pollution originates within the city cluster in IGP region and rest of the PM pollution is governed through long-range transport of pollutants from upwind region.

The PSCF maps of $PM_{2.5}/PM_{10}$ ratio identify potential source locations mainly in north-west directions such as Punjab, Haryana, with some contributions from Uttar Pradesh. This indicates that fine particles were transported predominately from regional source regions during autumn and winter season (Fig. 5.10a). In winter and autumn, the PSCF plots of CO/NO_x indicated that the probable locations

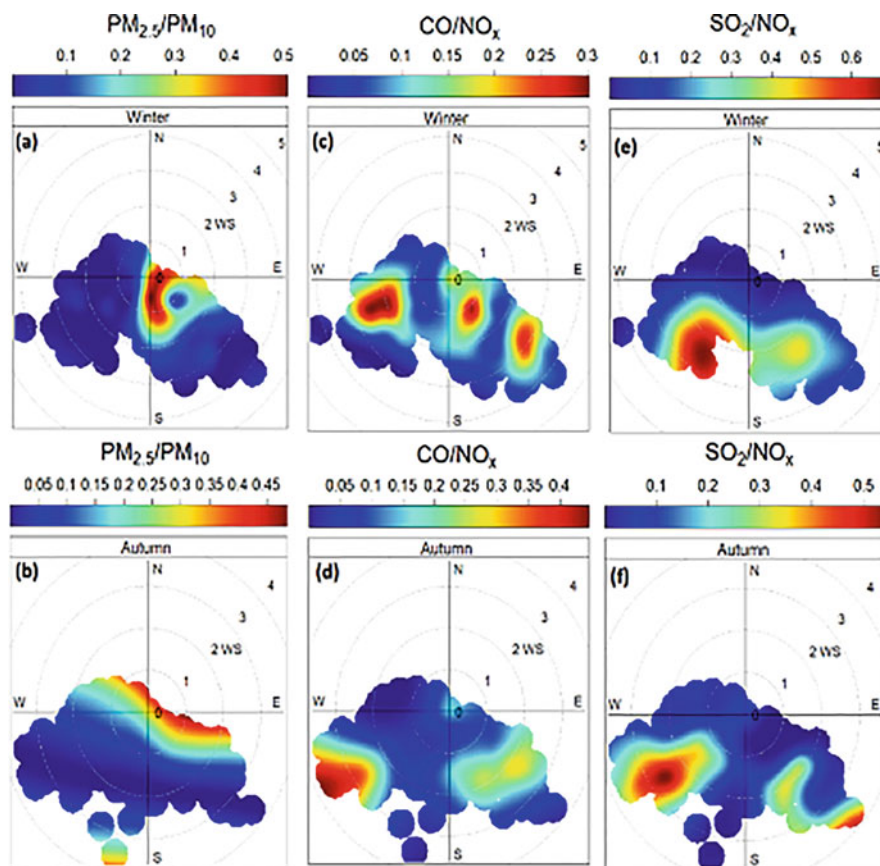


Fig. 5.8 CBPF plots of $PM_{2.5}/PM_{10}$, CO/NO_x and SO_2/NO_x in winter (top panel) and autumn (bottom panel) seasons over Mandir Marg in Delhi during year 2018. Threshold criteria were chosen at 75th percentile of species/pollutants

influencing their concentrations are situated in the south-east and east directions (Ghaziabad and Dadri from Uttar Pradesh) (Fig. 5.10b).

5.4 A Brief Review on Air Pollution and Public Health

5.4.1 Household Air Pollution (HAP) and Its Health Effects

According to the World Bank's 'The cost of air pollution: strengthening the economic case for action', it is estimated that health and productivity loss in India due to air pollution, ambient and indoor combined, was about 5.7% of the GDP in 2013 (Balakrishnan et al. 2019). The same report also estimates that of this 5.7%, the 1.3% of GDP loss was due to indoor air pollution (IAP).

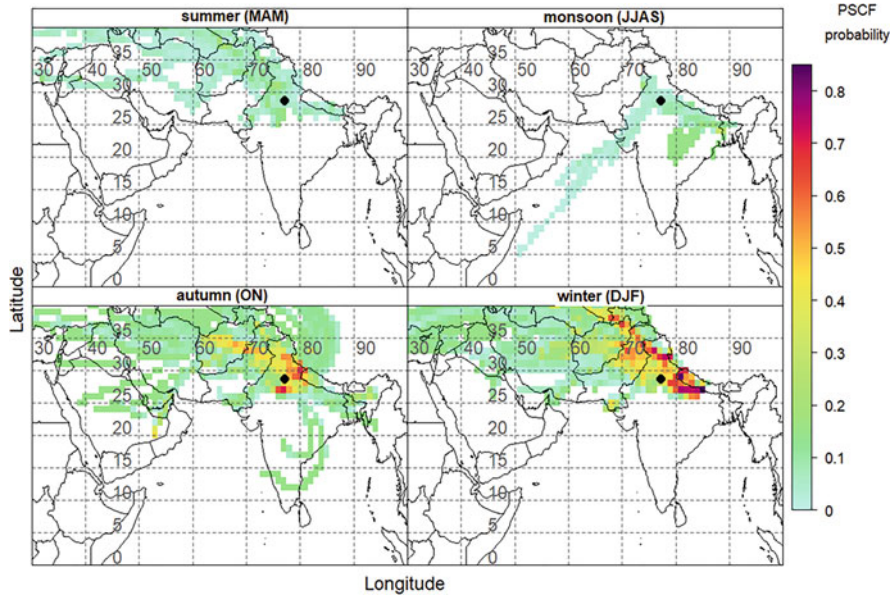


Fig. 5.9 PSCF plots of $PM_{2.5}$ using 5-day air mass back trajectories at Mandir Marg in Delhi (at 500 m above ground level). Threshold criteria were chosen at 50th percentile of pollutants

About IAP, the World Health Organization (WHO) asserts the rule of 1000, a rule which states that any pollutant released indoors is 1000 times more likely to reach into a person's lung as compared to the scenario when it is released outdoors (WHO 2007). As a result, IAP has been found to be 10 times more potent as ambient air pollution (Ching-Boon 2016). According to the WHO, IAP has directly been linked to increased cases of pneumonia, stroke, ischaemic heart disease, chronic obstructive pulmonary disease (COPD), and lung cancer in women and children (WHO 2018b).

Moreover, studies indicate that IAP disproportionately affects under-developed and developing countries (Kankaria et al. 2014). 4.5% of global daily-adjusted life year (DALY) and 3.5 million deaths in 2010 were attributed to indoor air pollution. The World Bank Study also reported that the total welfare loss due to premature death as a result of air pollution increased by 94% between 1990 and 2013, in which the contribution of IAP increased by four times to the final tune of \$1.5 trillion (adjusted to 2011 PPP, purchasing power parity).

5.4.2 Sources and Pollutants

- (a) Solid and biomass fuels—Incomplete combustion of biomass fuels generate pollutants like particulate matter (PM), carbon monoxide, polyaromatic hydrocarbons, polyorganic matter and formaldehyde. Combustion of coal, on the other hand, produces oxides of sulphur, arsenic and fluorine.

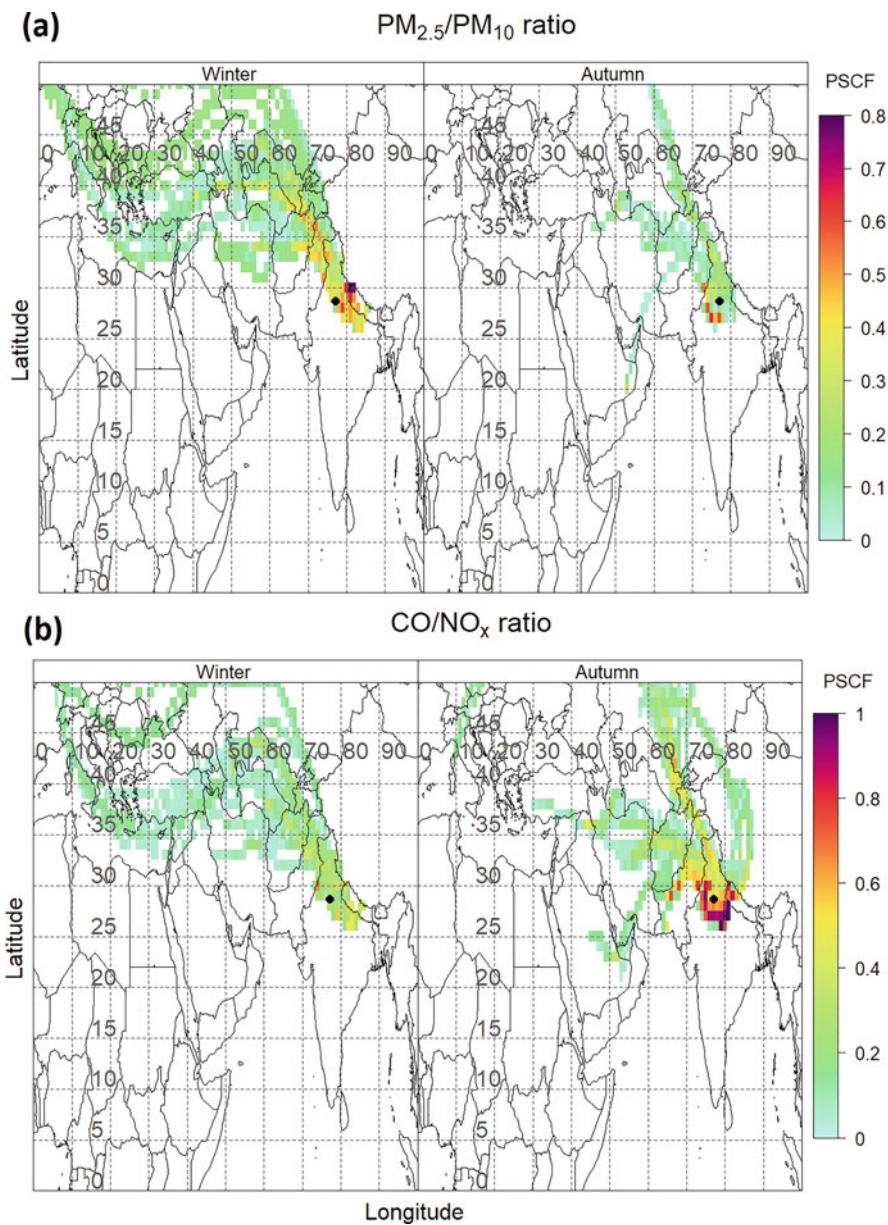


Fig. 5.10 PSCF plots of $PM_{2.5}/PM_{10}$ and CO/NO_x ratio at Mandir Marg in Delhi. Threshold criteria were chosen at 50th percentile of pollutants

Table 5.2 Indoor air polluting major cooking sources and associated emission impact from rural Indian region

Indoor pollution source	CO (mg m ⁻³)	PAH (mg m ⁻³)	HCHO (mg m ⁻³)
Dung cake	144	3.56	670
Wood	156	2.01	652
Coal	94	0.55	109
Kerosene	108	0.23	112
LPG	14	0.13	68

Table 5.3 Indoor air quality in buildings within Delhi NCR

Pollutants	Average concentration
CO ₂ , ppm	1068
PM ₁₀ , µg m ⁻³	689
PM _{2.5} , µg m ⁻³	492
Benzene, ppb	150
Acetaldehyde, ppb	3125
Acetone, ppb	800
Toluene, ppb	275
Aerobic plate count, CFU	153
Fungal count, CFU	48

Here, *ppm* parts per million; *ppb* parts per billion; and *CFU* colony-forming units

- (b) Bioaerosols—Airborne particles produced from microbial, viral, fungal and actinomycete, as well as microbes from organic materials, humidifiers, vaporizers, heating, ventilating and air conditioning systems (HVAC), lead to allergies, infections and poisoning.
- (c) Volatile organic compounds—Pollutants such as aldehydes, volatile and semi-volatile organic compounds from resins, waxes, polishing materials, cosmetics and binders.
- (d) Heavy metals like zinc, cadmium, chromium, mercury, lead and copper. Radon, pesticides, tobacco smoke and carbon monoxide.
- (e) Biological pollutants like dust mites, moulds, pollen and infectious agents produced in stagnant water, mattresses, carpets and humidifiers too pollute indoor air.
- (f) Infiltration of outdoor polluted air.

Additionally, indoor air quality (IAQ, Tables 5.2 and 5.3) gets further affected by

1. Building characteristics such as the air tightness and ventilation
2. Building occupancy and living space
3. Equipment used within the buildings (e.g. photocopiers, printers and heaters)
4. The customs, habits and tradition of the residents
5. The economic status of occupants

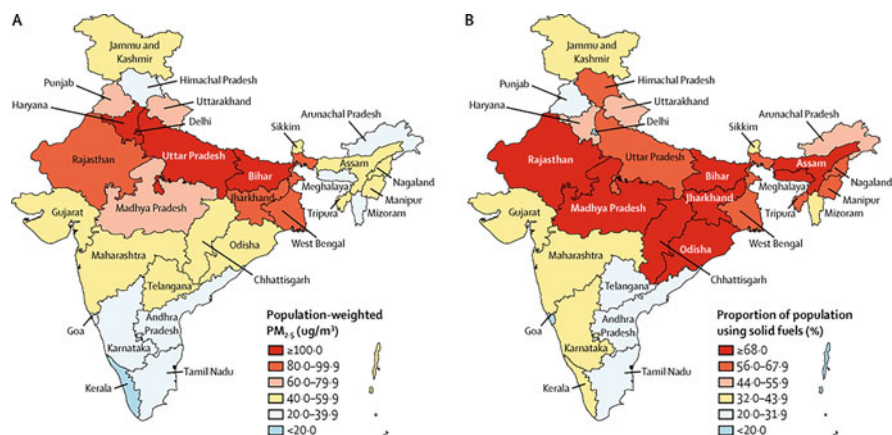


Fig. 5.11 $PM_{2.5}$ mass concentrations and use of solid fuels in the states of India, 2017: (a) Population-weighted mean ambient air $PM_{2.5}$ and (b) proportion of population using solid fuels. (Adapted from Balakrishnan et al. 2019)

In India, combustion of fuels is the largest contributor to indoor air pollution (IAP). Balakrishnan et al. (2019) find that IAP continues to wreak havoc in India due to excessive residential use of solid fuels (wood, dung, agricultural residue, coal and charcoal) for cooking and heating purposes (Fig. 5.11). Furthermore, more than half of India's population was exposed to IAP in 2017 (Balakrishnan et al. 2019).

5.4.3 Health Status

Of the 1.24 million deaths in India in 2017 due to air pollution (12.5% of all deaths in India that year), 0.48 million deaths were attributed to IAP (Balakrishnan et al. 2019). 8.1% of total DALYs in India (38.7 million in 480.7 million) for the same year were due to air pollution; 3.3% were due to IAP. Lancet report informs that 1 out of every 8 deaths in India in 2017 were due to air pollution (Balakrishnan et al. 2019). This indicates that air pollution puts a disproportionate health burden on India. This same fact also means that India has the most to gain by undertaking reforms. The same Lancet report informs that reduction in air pollution and bringing air quality level to minimum accepted level would add 1.7 years to the average life expectancy of Indian population.

According to the State of Global Air Report, 2019 (Health Effects Institute 2019), Indian region was observed to have the second highest concentration of indoor $PM_{2.5}$ averaging at $91 \mu g m^{-3}$ in South Asia (after Nepal's $100 \mu g m^{-3}$) in 2017. Even in 2017, 56% of the population was still using solid fuels. A study done in rural areas of India found that PM exposure in a household that uses biomass for cooking averaged at $231 \pm 109 mg m^{-3}$, compared to households that used cleaner fuel where the daily average exposure stood at $82 \pm 39 mg m^{-3}$ (Kankaria et al. 2014). The findings from the above-mentioned study are presented below:

A study conducted in Mumbai found that $PM_{2.5}$ average concentration from tobacco smoke was $363 \mu\text{g m}^{-3}$ at venues where smoking was allowed, compared to $97 \mu\text{g m}^{-3}$ where it was not (Raute et al. 2011).

Besides households, other settings where IAP is a cause of concern are schools, offices, and hospitals. A Greenpeace India report found that pollution levels in Delhi schools were five times higher than the safe limit recommended by WHO (Press Trust of India 2015). Other studies done in Delhi (Singh et al. 2017), Chennai (Nagendra and Harika 2010), Himachal Pradesh (Shree et al. 2019) and international experiences (WHO 2018b) all corroborate this finding and confirm that IAP level remains far worse inside the classroom than outside with exaggerated PM levels being the most threatening pollutant.

The Lancet (Stokel-Walker 2018) reports that 800,000 people globally die every year due to air quality issues at their workplace, and many more suffer due to the 'sick building syndrome' (EPA 1991), which includes headaches, cough, fever and chest pain caused due to contamination of air inside buildings. Lack of nationwide data in the Indian context makes it hard to comment on the corresponding figures for India, but a presentation given at Griha Summit summarizes the following with respect to buildings in NCR (Meattle 2016). Other studies in Rajasthan (Singhvi et al. 2019) support the finding of poor indoor quality in buildings.

The WHO reports that at any time 1.4 million people around the world are influenced with hospital-acquired infections (HAIs) and as many as 80,000 people around the world every year die due to HAI (Sidhu 2018). The IAQ and HAI incidence is dependent on factors like dimensional space, design features, cleaning and maintenance activities (Gola et al. 2019) and presence of bacteria, fungi, moulds and germs (Sidhu 2018). Emissions of pollutants ($PM_{2.5}$, PM_{10} , O_3 and NO) from nearby sources like road traffic and parking (Gola et al. 2019) also contribute to poor air quality in hospitals. A study done in hospitals in Chennai found high level of contamination of bioaerosols and pathogens in indoor air (Sudharsanam et al. 2008).

5.4.4 Health Effects

IAP disproportionately affects children, women and elderly (over the age of 60) because they spend most of their time at home and thus are exposed to pollutants for a longer period (Table 5.4). Sustained exposure of pregnant women has been reported to affect both the mother and the unborn. According to WHO factsheet, 3.8 million people globally die prematurely every year due to IAP. Among these, 27% are due to pneumonia, 18% due to stroke, 27% due to ischaemic heart disease, 20% due to COPD and 8% due to lung cancer (WHO 2018b).

Studies have found that the use of solid fuels causes acute respiratory tract infection and COPD, poor perinatal outcomes like low birthweight and stillbirth, cancer of nasopharynx, larynx, lung and leukaemia (Kankaria et al. 2014). PM and nitrogen dioxide have been found to cause respiratory infections. PM causes chronic bronchitis and COPD, while nitrogen dioxide affects lung function and causes wheezing. Sulphur dioxide too causes wheezing and exacerbates asthma, COPD

Table 5.4 Health effects of indoor air pollution (IAP)

Study and year	Important finding summary
Capistrano et al. (2017)	Found increased airway inflammation and oxidative stress when women are exposed to biomass smoke
Neogi et al. (2015)	HAP found to be strongly associated with neonatal mortality rate after adjustment ($\beta = 0.22$; 95% confidence interval [CI] = 0.09 to 0.35) for urban and rural areas combined. For rural areas, the association was significant ($\beta = 0.30$; 95% CI = 0.13 to 0.45) after adjustment
Sehgal et al. (2014a, 2014b)	Use of biomass fuel was associated with cataract 2.16 (1.42, 3.26) and stillbirths 1.26 (1.12, 1.43) in women
Burnett et al. (2014)	Risk estimate for male COPD incidence due to IAP PM _{2.5} was 1.90 (95% CI: 1.56, 2.32) and for females was 2.70 (95% CI: 1.95, 3.75)
Bhat et al. (2012)	Use of any other fuel except LPG was found to be associated with acute lower respiratory tract infection (OR = 26.3, 95% CI: 10.5–65.7)
CPCB (2018)	Women chronically exposed to biomass smoke—high risk of developing upper and lower respiratory symptoms, lung function impairment, COPD, pulmonary and systemic inflammation, CVD, depression and increased risk of lung cancer
Johnson et al. (2011)	Biomass fuel use found to be associated with COPD (OR = 1.24, 95% CI: 0.36–6.64)
Sreeramareddy et al. (2011)	High exposure of pregnant women to IAP associated with low birthweight of newborns (OR = 1.41, 95% CI: 1.27–1.55)
Bassani et al. (2010)	Biomass fuel use associated with child mortality between ages 1 and 4 (prevalence ratio: boys = 1.30, 95% CI: 1.08–1.56; girls = 1.33, 95% CI: 1.12–1.58)
Tielsch et al. (2009)	Use of biomass fuels associated with increased probability (49%) of low birthweight
Behera and Balamugesh (2005)	Use of solid fuel among non-smoking women led to increased chances of lung cancer (OR = 3.04, 95% CI: 1.1–8.38)
Saha (2005)	Age-related cataract associated with wood burning (OR = 2.12, 95% CI: 1.03–4.34)

and CVD (Cardiovascular disease). Carbon monoxide (CO) has been found to lead to low birthweight and perinatal death, while polycyclic aromatic hydrocarbon (PAH) has been found to lead to cancers of lungs, mouth, nasopharynx and larynx. These PAHs are released by the combustion sources, which also produce metal ions, both of which cause cataract.

Incomplete combustion of biomass also produces formaldehyde, which has been known to cause acute irritation and bronchitis, reduce vital capacity and act as a carcinogen that can cause leukaemia and lung cancer. India-specific studies show that use of biomass combustion for cooking leads to active tuberculosis (odds ratio: OR = 3.66, 95% CI: 2.82–4.50). In fact, 51% of all cases of active tuberculosis in the age group of 20 years and above could be attributed to smoke from cooking. Users of biomass fuels were also found to be at 50% excess risk of stillbirths and 1.5 times more likely to have low birthweight babies. On average, these babies weigh 73 g lighter (mean birthweight 2883.8 g versus 2810.7 g, $p < 0.001$). There is also an

increased risk to asthma (Sehgal et al. 2014a, b). Besides this, the cognitive abilities and productivity levels of those exposed to higher level of indoor pollutions are severely hampered. Holding constant other risk factors, apart from LPG, all other cooking fuels were found to cause acute lower respiratory tract infection (adjusted OR = 4.73). In fact, the use of biomass fuels was found to significantly contribute to a prolonged nasal mucociliary clearance time (765.8 ± 378.16 s) when compared to the use of cleaner fuels (545.4 ± 215.55 s). Similarly, biomass use was also found to lead to higher cases of COPD (OR: 1.24), especially among those who spend more than 2 h a day for cooking. Additionally, the carcinogens (PAHs, HCHO, etc.) released by biomass fuels reportedly led to cases of lung cancer in women (Kankaria et al. 2014). Among women, the study conducted by Sehgal et al. (2014a, b) found that IAP contributes to 2.4 million of the 5.6 million cases of chronic bronchitis, 0.3 million of the 0.76 million cases of TB and five million of the 51.4 million cases of cataract. Her paper also corroborates aforementioned IAP health effects of COPD (OR from 1 to 3.04), lung cancer (OR from 1.5 to 3.8) and acute lower respiratory tract infections (OR from 1.5 to 3.7).

Studies that have been used to present above the health effects of IAP have been tabulated in table 5.4:

5.4.5 Vulnerable Population

IAP is more likely to affect rural and poor/low socio-economic status (SES) households compared to urban and richer households and women and younger children are the more vulnerable population compared to men (Kankaria et al. 2014). Since combustion of cooking fuels contributes to IAP the most, women get disproportionately affected due to household air pollution. According to the Global Burden of Disease programme, globally India records the highest number of deaths attributed to illnesses caused due to IAP from solid fuel burning. According to the World Health Organization's report 'Air Pollution and Child Health' in 2016, indoor air pollution led to the death of 66,890 children below the age of 5 years, out of which 36,073 were girls and 30,817 were boys. In totality, 101,788 children in India under 5 years of age died due to ambient and indoor air pollution combined, which roughly translates to around 12 deaths per hour in 2016. Besides women and children, it is the elderly (age ≥ 60 years) who are extremely vulnerable to IAP and studies show that the elderly in households that use biomass fuels more often suffer from asthma (as compared to households that use cleaner fuels, OR = 1.59; 95% CI: 1.30–1.94). The same study also confirmed that women are more vulnerable to asthma caused by IAP as compared to men.

5.5 Conclusions

We have presented here the current status of air pollution focusing over a typical urban site of Delhi and a brief overview of health effects of air pollution. We report on detailed characterization of the air masses in Delhi and investigate the following aspects: (i) temporal variability of particulate matter (PM_{2.5} and PM₁₀) on an hourly, weekly, monthly and seasonally basis; (ii) the primary and secondary pollutants and their relative abundances; and (iii) conditional probability function (CPF) and potential source contribution function (PSCF) are also discussed for the data set over Delhi. In Delhi, clear seasonal trends were observed for PM_{2.5}, PM₁₀, CO, SO₂ and NO_x. High abundance episodes of PM_{2.5}, PM₁₀, CO and NO_x were observed in winter and autumn due to emissions from local and regional sources and from the long-range transport. High PM_{2.5}/PM₁₀ ratio in autumn and winter is attributable to predominant impact from anthropogenic emission sources. CPF and PSCF analysis showed that besides local sources the long-range transport affected the local and regional ambient air quality in Delhi. Overall, the PSCF analysis has revealed that by and large the high concentration of air pollutants, mainly during the winter and autumn seasons, was associated with air masses arriving from north-west direction in Delhi. This study highlights the utility of other CAAQM stations in India for the exploration of air quality research, public health and awareness and policy framework.

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